B,V Photometry of Variable Stars in the Northeast Arm of the Small Magellanic Cloud

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ABSTRACT

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B and V photometry has been obtained for variable stars in the northeast arm of the Small Magellanic Cloud (SMC). Periods and lightcurves have been determined for 237 periodic variables, including 201 Cepheids, 68 of which are newly discovered. Fundamental mode Cepheids and first overtone mode Cepheids are generally well separated in the B, V color-magnitude diagram, with the latter having bluer mean colors than the former. The Cepheid period-color relationship for this outlying SMC field is indistinguishable from that seen in more centrally located SMC fields, and is bluer than theoretical predictions. The red edge to the populated portion of the instability strip shifts to bluer colors for fainter Cepheids. There is support from our sample for a previously reported steepening in the slope of the period-luminosity relation for fundamental mode Cepheids near a period of 2 days. The Cepheids of the northeast arm may be closer to us than are those of the main body of the SMC, but the difference is smaller than or equal to about 4 kpc, comparable to the tidal radius of the SMC.

Subject headings: Stars:Variables:Cepheids; Galaxies: Magellanic Clouds

1.   Introduction

Leavitt (Pickering 1912) discovered the period-luminosity relation using observations of Cepheid variable stars in the Small Magellanic Cloud (SMC). Because the young population of the SMC is now known to be metal-poor relative to that of the solar neighborhood and to that of the Large Magellanic Cloud, SMC Cepheids remain of particular interest in the elucidation of the effects of metallicity upon the properties of Cepheid variable stars. Moreover, it has been proposed that the depth of the SMC along the line of sight is not insignificant compared to its mean distance (Westerlund 1997 and references therein). Cepheids provide a means of measuring the distances to the young populations of different parts of the SMC.

Smith et al. (1992) used photographic photometry in the B band to study the variable star population in an outlying field in the northeast arm of the SMC centered on RA = 1^h03^m and DEC = $-71°23'$ (J2000). The brighter variable stars within this field have been studied by Arp (1960) and Payne-Gaposchkin & Gaposchkin (1966), who concentrated primarily on the variable stars discovered previously at Harvard. Extending the search for variable stars to fainter limits, Smith et al. (1992) identified 136 new variables in the area and obtained photographic B light curves for 150 new and old variables. Their period-luminosity diagram showed the presence of both fundamental mode and first overtone mode Cepheids, but, because they observed only in the B band, they could not address questions regarding the colors of the variable stars they observed.

We have obtained B and V CCD photometry of variable stars in this field, including 84 newly discovered variables, 63 variables first observed in Smith et al. (1992), 2 variables present in the Clement et al. (2001) catalog of globular cluster variable stars, as well as 88 Harvard variables. Our purpose in carrying out this survey was to address several issues. First, the present CCD survey more readily detects low amplitude Cepheids than did the earlier photographic study, providing a more complete picture of the variable star population of the northeast arm. Second, the new data allow us to discover where the fundamental mode and first overtone mode Cepheids fall within the color-magnitude diagram (CMD). In particular, is there overlap beyond that attributable to observational error in the colors of Cepheids having different pulsation modes, or do fundamental mode and first overtone mode Cepheids occupy distinct and separate regions in the CMD? A substantial overlapping of the fundamental mode and first overtone mode Cepheid domains is visible in the $I_0, (V-I)_0$ CMD based upon data taken in the OGLE II survey (Figure 4 of Udalski et al. 1999b). However, that survey emphasized the crowded central regions of the SMC, and problems with crowding, blended images, and possibly differential reddening may have contributed to the overlap. If that overlapping is real, and not attributable to observational error, then there is no unique dividing line between fundamental mode and first overtone mode SMC Cepheids in the HR diagram. The existence of a hysteresis zone, in which pulsation mode depends upon direction of evolution in the HR diagram, would be one possible way by which such an overlap zone might be produced. Such a hysteresis zone has been proposed for RR Lyrae variables (e.g., Stellingwerf 1975).

In addition, prior studies have found a break in the slope of the period-luminosity $(P-L)$ relation for fundamental mode SMC Cepheids near a period of 2 days (see § 8). This break has not yet been satisfactorily explained, and it is of interest to determine whether the location of the short period Cepheids in the CMD can shed light upon this problem. We also want to compare the period-color relations for Cepheids in the northeast arm with those which have been derived for Cepheids in more central regions of the SMC and with theoretical period-color relations.

Finally, we wish to compare the $P - L$ relations for the northeast arm Cepheids with those derived in the course of microlensing surveys of more central SMC fields. If the slopes of the $P - L$ relations derived for Cepheids in the northeast arm are significantly different from those of Cepheids in the main body of the SMC, that would indicate that the Cepheid population of the SMC is heterogeneous, with properties depending upon location. Alternatively, a difference only in the zero-points of the $P - L$ relations might indicate that the Cepheids of the northeast arm are nearer or more distant than those in other parts of the SMC.

2.   Observations and Reductions

Four fields in the northeast arm of the SMC were imaged with the Thomson 1024×1024 CCD camera on the CTIO 60-cm Curtis Schmidt telescope. Each field measures 0.5 degrees on a side, together defining a square $1° \times 1°$ area of the SMC centered approximately on RA $= 1^h03^m$ and DEC $= -71°23'$ (J2000), including most of the field studied photographically by Smith et al. (1992). There are small areas of overlap between our adjoining fields. Our pixel size was approximately $2''$ square. For comparison, the pixel size for the detector utilized by the OGLE group in their microlensing survey (OGLE II), to which comparisons are made in this paper, was approximately $0.4''$ square, although they were limited to a seeing resolution of about $1''$ in the visible bands due to non-uniformities in telescope tracking complicating the driftscan-mode acquisition of their detector (Udalski et al. 1997).

The four fields were observed with Johnson B and V filters during five runs in 1992, 1993, and 1994. A journal of observations for these observing runs is provided in Table 1. During the first runs in September and October, 1992, the usual observing procedure was to obtain three consecutive V and four consecutive B exposures of each field, each 300 s long. These were later combined to constitute one 900 s V and one 1200 s B observation. During runs in September and November, 1993, and October, 1994, the exposure times in B were increased to 420 seconds, so that the total exposure from the combination of four consecutive B images was 1680 s. Because of the poorer blue sensitivity of the Thomson chip, the B images do not reach as faint as the V despite the longer exposure times.

Images were flattened with sky flats, and conventionally reduced with IRAF [4]. Aperture photometry was obtained with the standalone version of DAOPHOT II (Stetson 1987). Because the CCD pixels are $2''$ square, confusion of images can be a significant source of error in the more crowded portions of the fields.

The photometry for the individual frames was first reduced to an adopted instrumental magnitude system. Possible variable stars were then identified from the scatter about the mean value in the instrumental b and v magnitudes. Examination of the images of suspected variables eliminated those stars for which the scatter could be attributed to crowding or other causes not related to true variability. Typically, each variable was observed about 22 times in each filter, although a few variables in the overlap zones between fields were observed more frequently. Quantitatively estimating the completeness of this survey is difficult, given stars are lost due to magnitude, amplitude, and period considerations as well as confusion in

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[4]IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

crowded images. Nevertheless, Cepheid variable stars with periods under 20 days, amplitudes greater than about 0.2 mag, apparent magnitudes brighter than $\langle V \rangle = 18.5$, and which were not subject to severe crowding, should have been detected in this search. The completeness of variable star identification declines sharply at magnitudes fainter than 18.5, even for uncrowded stars. The identification of SMC RR Lyrae variables, at $\langle V \rangle \sim 19.5$, is very incomplete, and only 5-10% of the SMC RR Lyrae stars within the field are likely to have been detected. Completeness also declines in the most crowded regions of our fields, particularly affecting the most southerly areas of the survey. We still would expect to identify most SMC Cepheids of $\langle V \rangle \leq 17.5$, even in crowded fields, although the measured light curves might not be of high quality.

A period search was conducted for the suspected variables using the phase dispersion minimization program, as implemented in IRAF. The spacing of our observations is well-suited for determining periods for stars which have periods shorter than about 5 days, but is not well suited for longer periods. Determinations of periods longer than 20 days are not possible with any reliability. Hodge & Wright (1977), Smith et al. (1992), and Clement et al. (2001) were consulted to identify known variable stars within our fields. Although the periods for most of these previously discovered variables are already known, a new period search was nonetheless carried out for each of them.

Newly discovered variables are identified in Figures 1a-1d. Positions for the new variables were calculated on the system of the Digitized Sky Survey, using routines in IRAF. The resultant positions, good to about 2″, are listed in Table 2. The error was estimated from comparisons of the positions we derived with those listed in the MACS catalog (Tucholke et al. 1996) for stars in common. The numbering scheme for the new variables is prefixed with "SSP" and numbers 84 stars.

Local standards were set up in a single $13.6' \times 13.6'$ field, centered on RA = $01^h04^m49^s$, Dec = –71°23′00″ (J2000), with the CTIO 0.9-m telescope and CCD imaging system on 8 November 1999. CCD SITe 2048 #3 was used together with the standard 0.9-m $UBVRI$ filter set. Observations of the standard field were made in U, B, V, I filters, of which only B and V are relevant for the calibration purposes required here. Exposure times were 2×100s, 500s (V) and 2×200s, 1000s (B). Twilight sky flat field exposures successfully reduced systematics to well below one percent.

The night was photometric and observations were made of 105 Landolt (1992) standards in 10 fields at a variety of airmasses ranging from 1.07–1.85. Of these stars a few, with large previously measured residuals (Landolt 1992) or which fell into CCD defects, were rejected. However, 86 were retained in the final color equation fits, which confirmed the high quality of the night, with zeropoints constrained to 0.0015 – 0.002 mag.

A set of 21 local standards, selected as being isolated stars covering a wide magnitude and color range ($V : 12-17, B-V : -0.2-+1.5$) were measured using aperture photometry in exactly the same way as the primary standard stars, in airmasses between 1.33 and 1.35. Stars brighter than magnitude 13.5 were measured on the short exposures only; the remaining stars all have three measurements. Agreement between measurements for any given star is typically 0.01 mag. Photometry and positions for the local standards are listed in Table 3. Results are listed individually for the two shorter and one longer exposures. Values of right ascension and declination were found in the same fashion as for the new variable stars. The local standard stars are identified in Figure 2.

Instrumental b and v magnitudes were transformed to the Johnson B and V systems using the local standard stars. Transformation equations had the form:

$$b = B + C_B - 0.05(B - V), \tag{1}$$
$$v = V + C_V - 0.01(B - V). \tag{2}$$

Two existing photometric sequences were used to check the accuracy of the transformation. Our two more northern fields include stars near NGC 362 which were observed photoelectrically and photographically in B and V by Harris (1982). Secondly, one of our fields includes the SMC cluster NGC 411, for which Da Costa & Mould (1986) obtained B, R photometry. Mean differences between our B and V values and those in Harris (1982) and Da Costa & Mould (1986) are summarized in Table 4. The number of stars compared and the mean differences in the magnitudes, in the sense their values minus ours, are listed in this table. The different photometric systems appear to agree to within about $\pm$ 0.02 mag. The photometry for individual variable stars is listed in Table 5. The full table will be given in the electronic version of this paper. The errors listed in column 4 of this table are the formal standard errors returned by the DAOPHOT II code, and may in some cases underestimate the actual uncertainty.

3. Lightcurves, Periods, and Mean Colors

Data for the periodic variables observed in this survey are summarized in Table 6. The variable is identified in column (1) by its Harvard Variable number (HV), its designation in the Clement et al. (2001) catalog (NGC362V), its number in Smith et al. (1992) ([SSB92]), or by its number in Table 2 (SSP). The variable type is listed in column (2), where "F" indicates a Cepheid pulsating in the fundamental mode, "O" indicates a Cepheid pulsating in the first overtone mode, "RRab" indicates an RR Lyrae star in the fundamental mode, "RRc" indicates an RR Lyrae star in the first overtone mode, and "E" indicates an eclipsing

variable star. Our derived period, typically good to a few parts in 10^5, is given in column (3). We list luminosity-weighted mean $\langle B \rangle$ and $\langle V \rangle$ magnitudes in columns (4) and (5). Luminosity-weighted $\langle B \rangle - \langle V \rangle$ and magnitude-weighted mean $(B-V)_{mag}$ colors are listed in columns (6) and (7). In column (8) a "1" signifies a variable with a relatively complete and well defined lightcurve, whereas a "2" indicates that the lightcurve is noisy or has substantial gaps. In general, only stars with quality "1" lightcurves were selected for more detailed analysis. For a few variables, a good lightcurve was obtained in B or V, but not in both bandpasses. These are indicated by a "1(V)" or "1(B)" in column (8). A cubic spline was fit to each lightcurve and used to calculate all mean magnitudes and colors.

The decision to assign a Cepheid to the first overtone or fundamental mode category was made by inspection of the lightcurves. Previous studies have indicated that, at a given period, the lightcurves of first overtone pulsators are characterized by smaller amplitudes and less asymmetry than those of fundamental mode pulsators (e.g. Smith et al. 1992). Classifications of pulsation mode based on lightcurves appear to be fully consistent with the locations of the Cepheids in the period-luminosity domain. The number of data points for most of the Cepheids is not large enough to effectively apply Fourier decomposition methods for determining pulsation mode. It is also possible that some of the Cepheids, particularly among the quality "2" group with periods less than a day, may be double-mode pulsators. Double-mode Cepheids have been discovered in both the LMC (Alibert et al. 1999; Soszyński et al. 2000) and SMC (Beaulieu et al. 1997). However, we do not have a sufficiently large number of observations to effectively test for double-mode behavior among these stars.

B and V lightcurves for periodic variables are shown in Figure 3, arranged in order of descending period. Phases have been calculated from the formula:

$$\phi = (JD_{\odot}/P) , \tag{3}$$

where $JD_{\odot}$ is the full heliocentric Julian Date and P is the period in days, with only the non-integer part of the quotient retained as the phase. Pulsating variables of all types with quality "1" lightcurves in both B and V are plotted in the $\langle V \rangle - \log P$ diagram in Figure 4.

4. Reddening

Harris (1982) adopted $E(B-V) = 0.04$ for the globular cluster NGC 362, which is located close to our northeast arm field. Da Costa & Mould (1986) also adopted $E(B-V) = 0.04$ for NGC 411, which is within our field. Caldwell & Coulson (1986) found a mean

reddening of $E(B-V) = 0.054$ for all except the central region of the SMC. Grieve & Madore (1986) obtained $E(B-V) = 0.09$ for SMC supergiants, with no trend with location in the SMC. Based upon these results, Smith et al. (1992) adopted a mean reddening of $E(B-V) = 0.06$ for the northeast arm region. More recently, Udalski et al. (1999b) obtained reddening values of $E(B-V) = 0.079$ and 0.084 for their SMC fields SC10 and SC11, the two fields in their survey which are closest to our own. Both SC10 and SC11 lie nearer to the central body of the SMC than does our field. SC10 is centered at RA $= 1^h04^m51^s$, DEC $= -72°24'25''$ (J2000), and SC11 is centered at RA $= 1^h07^m45^s$ and DEC $= -72°39'30''$ (J2000). Udalski et al. (1999b) assigned $E(B-V) = 0.070$ to their field SC1 which, although on the sky it lies on the other side of the SMC from the northeast arm, may be the OGLE II field most similar to our own in terms of stellar density.

We can also estimate the foreground reddening in the direction of the northeast arm using the color data for Galactic RR Lyrae stars within our field. Sturch (1966) and Blanco (1992) determined that the intrinsic colors of ab type RR Lyrae stars were a function only of metallicity, period, and average color in the phase interval $0.5 \leq \phi \leq 0.8$ after maximum light. Here we employ the relationship, found by Blanco (1992), that the reddening within this phase interval is given by:

$$
\begin{aligned}
E(B-V) \ = \ & \langle B-V \rangle_{\phi(0.5-0.8)} + 0.0122 \Delta S \\
& - 0.00045 (\Delta S)^2 - 0.185 P - 0.356 \,,
\end{aligned} \tag{4}
$$

where P is the period in days and ΔS is the spectroscopic metallicity index for RR Lyrae stars (Preston 1959). Unfortunately, we have no direct measurement of the metallicity index ΔS for the foreground RR Lyrae stars. An indirect estimate of ΔS for these variables can be made from the period shift of the star, $\Delta \log P$, as defined in Sandage (1982b):

$$
\Delta \log P \ = \ -[\log P + 0.129 A_B + 0.088] \,, \tag{5}
$$

where A_B here is the B amplitude, not the B band extinction. $\Delta \log P$ is related to [Fe/H] by the relation (Sandage 1982a):

$$
\Delta \log P \ = \ 0.116 [\text{Fe/H}] + 0.173 \,. \tag{6}
$$

If we employ the calibration of the ΔS index from Butler (1975):

$$
[\text{Fe/H}] \ = \ -0.23 - 0.16 \Delta S \,, \tag{7}
$$

ΔS can then be related to observable parameters and substituted into the Blanco (1992) formula to determine reddening. Values of $E(B-V)$ determined in this fashion for foreground RRab stars are listed in Table 7, along with the inferred values of [Fe/H]. Some

uncertainty attaches to this approach, particularly as it is applied to individual stars, since $\Delta \log P$ also may depend upon the evolution of the particular star under consideration. The mean value of $E(B-V)$ derived in this way is 0.05±0.01. The formal error of the mean is undoubtedly an underestimate given the uncertainty which attaches to our determination of the metallicities. If our derived [Fe/H] values were systematically in error by 0.4 dex, the derived mean value of $E(B-V)$ would change by 0.03, which is a more realistic estimated uncertainty. Although in principle the same approach can be used to determine reddenings for RRab stars actually belonging to the SMC, our lightcurves for such stars are too noisy to permit us to use them in that fashion. A foreground reddening of $E(B-V) = 0.05$ is greater than the value of 0.019 ± 0.004 found by McNamara & Feltz (1980) from photometry of foreground stars in the direction of the SMC, but is similar to the 0.04 adopted by Harris (1982) for NGC 362.

For the remainder of this paper we adopt a reddening value $E(B-V) = 0.07$ for the northeast arm field, a value slightly larger than the reddening determined for the foreground RRab stars, and close to the values Udalski et al. (1999b) obtained for outlying parts of the SMC. The adopted value of $E(B-V)$ may be uncertain by ±0.02, an uncertainty which encompasses the most recent determinations of the reddening in the direction of the SMC. We follow Udalski et al. (1999b) in adopting the relations:

$$
\begin{aligned}
A_B &= 4.32\, E(B-V)\,, &\text{(8)}\\
A_V &= 3.24\, E(B-V)\,, &\text{(9)}
\end{aligned}
$$

giving $A_B = 0.30$ and $A_V = 0.23$.

5.   Period-Frequency Relations for Cepheids

Table 8 lists the distribution of the number of fundamental and first overtone mode Cepheids as a function of period for variables in the present survey and in the survey of Smith et al. (1992), which covered a larger $1° \times 1.3°$ area. In this table we include all variables with periods, not just those with quality "1" lightcurves. This comparison is shown graphically in Figure 5. Allowing for the larger field size of the Smith et al. photographic study, we see that the present survey identified a modest but significant number of additional fundamental mode Cepheids which were not included in Smith et al. (1992). In contrast, the number of first overtone mode pulsators with periods has been approximately doubled. This can be attributed to the greater ease of identifying low amplitude variables using the CCD images. Somewhat surprisingly, the greatest number of additional first overtone Cepheids occurred in the $0.3 < \log P_1 < 0.4$ bin, among the brighter first overtone Cepheids. Figure 6 compares

histograms for all Cepheids with periods and for those with quality "1" lightcurves. Note that first overtone Cepheids with quality "1" lightcurves tend to be under-represented at periods close to one day. This reflects the difficulty in obtaining complete phase coverage for variables with one day periods. The quality "2" first overtone Cepheids do cluster around one day for the same reason. Likewise, lack of complete phase coverage is responsible for the deficit of quality "1" lightcurves among the longer period fundamental mode Cepheids.

The maximum number of fundamental mode Cepheids was observed in the $\log P_0 = 0.2 - 0.3$ bin. This is very close to the most common period in the histogram (Figure 6, Udalski et al. 1999b) over $\log P$ for fundamental mode Cepheids in the more central parts of the SMC studied in the OGLE II survey. The period-frequency distribution for fundamental mode Cepheids in the northeast arm is similar in general to that seen in the areas surveyed in OGLE II.

In our study, the first overtone mode Cepheids exhibit a broad peak, cutting off sharply at periods longer than $\log P_1 = 0.4$. Udalski et al. (1999b) also found a relatively broad peak in their histogram (also their Figure 6) over $\log P_1$ for first overtone Cepheids in the SMC. However, their cutoff at longer periods is not so sharp as is shown in Table 8, and their histogram is more strongly peaked to periods around $\log P_1 = 0.1$. We note, however, that with the smaller number of first overtone Cepheids in our sample, this difference may not be significant.

6.   Color-Magnitude Diagram

In Figure 7, we plot luminosity-weighted, extinction-corrected mean V magnitudes, $\langle V \rangle_0$, against magnitude-weighted, reddening-corrected mean colors, $(B-V)_{mag,0}$, for those Cepheids in Table 6 which have quality "1" B and V lightcurves. We choose to plot magnitude-weighted, rather than luminosity-weighted colors here since, at least for RR Lyrae stars, it has been argued that magnitude-weighted colors are closely related to the equilibrium temperatures of the stars (De Santis 2001). As is evident from Table 6, the magnitude-weighted and luminosity-weighted colors are in any case similar (though with small differences dependent upon lightcurve shape). The $(B-V)_{mag}$ colors tend to be about 0.01–0.02 mag redder than $\langle V \rangle - \langle B \rangle$ colors for the variables we observed. For galactic Cepheids, Bono et al. (1999) predict a difference of 0.018 mag at $\log P = 1.0$.

As expected, the Cepheids fall within a well-defined instability strip. The first overtone Cepheids are for the most part well divided from the Cepheids which pulsate in the fundamental mode. There is some overlap at the boundary between first overtone and fundamental

mode pulsators, but the overlap is mostly small, and can be accounted for by typical errors of $\pm$ 0.03 mag in $(B-V)_{mag}$. A few stars are, however, significantly bluer or redder than would be expected on the basis of their pulsation mode. Arp (1960) noticed that HV1898 has an unusually blue color compared to other Cepheids of similar lightcurve shape and period, a result with which we concur. He attributed this to the presence of an unresolved blue companion, a conclusion which seems very plausible. It is quite possible that all of the color overlap between fundamental mode and first overtone mode Cepheids in Figure 7 can be attributed to the combination of observational errors and the existence of a few instances of unresolved companions. There is evidence for a narrowing of the Cepheid instability strip, or at least the populated region of the instability strip, at lower luminosities, with the red edge shifting to bluer colors for fundamental mode Cepheids.

For comparison, Figure 8 shows a color-magnitude diagram in which points for the Cepheids in Udalski et al.'s (1999b) fields SC10 and SC11 are added to those in our field. We note that the OGLE project web page states that the photometry for the SMC Cepheids was revised on April 1, 2000. We have used the revised photometry throughout this paper (Udalski et al. 2000).

The pattern in Figure 8 is similar to that in Figure 7: Fundamental mode pulsators tend to have redder colors than first overtone pulsators of equivalent luminosity. There is more scatter than in Figure 7 and a greater overlap in color between fundamental mode and first overtone mode Cepheids. That can plausibly be attributed to a greater proportion of crowded star images or incomplete lightcurves in the somewhat more central SC10 and SC11 fields than in the selected data used to make Figure 7. One possibly significant difference between the two color-magnitude diagrams is the existence of a number of faint and relatively red first overtone pulsators at the bottom of the color-magnitude diagram (Figure 8) from the OGLE II sample which are not seen in our dataset. The OGLE II B and V lightcurves of some of these redder first overtone stars are noisy, but that is not the case for all of them. These variables have $\langle V \rangle_0 \sim 18$ and extend to $(B-V)_{mag,0} = 0.4$. It is true that some of our shorter period first overtone Cepheids were excluded from Figure 7 and Figure 8, on the basis that their lightcurves showed too much scatter (see Table 6). However, we would expect that at least a few of the faint, redder first overtone variables would have been well-observed in our dataset were such stars as common in our field as they seem to be in SC10 and SC11. We also note that there remains evidence for a blueward shift in the colors of the reddest fundamental mode Cepheids as one goes to fainter luminosities. This will be discussed further in § 8.

7. Period-Color Relations

We have determined least squares fits to the period-color relations defined by the fundamental mode and first overtone mode Cepheids within our northeast arm field. To uncorrelate the errors in slope and zero-point, we fitted about the median period of each distribution. For 70 fundamental mode Cepheids with reliable colors, meaning quality "1" light curves in both bands, we obtain:

$$(B-V)_{mag,0} = 0.27(\pm0.03)(\log P_0 - \overline{\log P_0}) + 0.42(\pm0.01) \,, \tag{10}$$

where $\overline{\log P_0} = 0.3631$, producing a standard deviation of $\pm$ 0.05 mag to the fit. For 58 first overtone mode Cepheids with reliable colors we find:

$$(B-V)_{mag,0} = 0.14(\pm0.03)(\log P_1 - \overline{\log P_1}) + 0.31(\pm0.01) \,, \tag{11}$$

where $\overline{\log P_1} = 0.1918$, yielding a standard deviation of $\pm$ 0.04 mag to the fit. To cast these relations in a form more easily comparable with theoretical period-color relations we have refitted our data without the offset by median period, obtaining:

$$(B-V)_{mag,0} = 0.27(\pm0.03)\log P_0 + 0.32(\pm0.01) \,, \tag{12}$$

for fundamental mode Cepheids and

$$(B-V)_{mag,0} = 0.14(\pm0.03)\log P_1 + 0.29(\pm0.01) \,, \tag{13}$$

for first overtone mode Cepheids. For comparison we include our least squares fits to 1250 fundamental mode Cepheids and 773 first overtone mode Cepheids in Udalski et al. (1999b):

$$(B-V)_{mag,0} = 0.27(\pm0.01)\log P_0 + 0.32(\pm0.01) \,, \tag{14}$$

$$(B-V)_{mag,0} = 0.18(\pm0.02)\log P_1 + 0.301(\pm0.004) \,. \tag{15}$$

The period-color relations for the fundamental mode and first overtone Cepheids are shown in Figures 9 and 10. Our period-color relations and those defined by stars in the more centrally located OGLE II fields are in excellent agreement for the period ranges covered by our data. The agreement is not so good with the theoretical period-color relation for fundamental mode SMC Cepheids (Z = 0.004) taken from Alibert et al. (1999), which is significantly redder than the observed relations. The slope of the period-color relation for fundamental mode Cepheids of Z = 0.004 from Caputo et al. (2000) is closer to that which is observed, but the zero-point is slightly too red. A reduction of 0.04 in the adopted value of E($B-V$) would bring the observed period-color relationship into good agreement with that of Caputo et al. (2000). A change that large is probably unlikely, but an error of 0.02 in the adopted reddening value can certainly not be excluded. The theoretical period-color relationships of Alibert et al. (1999) and Caputo et al. (2000) are plotted in Figure 9.

8. Period-Luminosity Relations

We have fit B and V period-luminosity $(P-L)$ relations of the form $M = \alpha \log P + \beta$ to the data for the fundamental mode and first overtone Cepheids, using all the Cepheids from Table 6 with quality "1" photometry in the relevant passbands. Luminosity-weighted $\langle B \rangle_0$ and $\langle V \rangle_0$ magnitudes have been used in these fits and no outliers have been excluded. Coefficients from least squares and least absolute deviation fits are listed in Table 9. The values of σ listed for the least squares fits are the usual mean errors. Those listed for the least absolute deviation fits are a measure of the mean absolute deviation. The period-luminosity relations are plotted in Figures 11, 12, 13, and 14.

The least squares and least absolute deviation fits are almost indistinguishable from one another and return coefficients which are well within the uncertainties of the coefficients in the least squares fits. The scatter about the relationships, as measured by the residuals (σ) from both methods, is similar. Some of the scatter will, of course, be real – reflecting the existence of a finite width to the Cepheid instability strip in the HR diagram. Some of the scatter in the relationships may also be the result of differential reddening across our four fields constituting our northeast arm field. Given the outlying location of our SMC field, and the relatively small range in SMC reddening found by Udalski et al. (1999b), the likelihood of a large range of reddenings for individual stars is probably small. Nonetheless, differential reddening cannot be entirely dismissed as a possible cause of scatter.

To check for the effect of differential reddening, we have calculated the extinction-insensitive Wesenheit index, W_{BFM}, (Madore & Freedman 1991) for each of the Cepheids, where

$$W_{BFM} \;=\; V - 3.24 \times (B-V) \,. \tag{16}$$

The coefficients of fits to the W_{BFM} versus $\log P$ diagrams are given in Table 10 and the relations are plotted in Figure 15. The scatter of the $W_{BFM} - \log P$ relation isn't smaller than that for the extinction-corrected $\langle V \rangle - \log P$ relations; indeed it is even larger for the first overtone Cepheids, though the difference is not statistically significant. Nevertheless we are reassured that the scatter in the $P-L$ relations for B and V is not attributable to differential reddening across our field.

The coefficients of the $P-L$ relations derived from our data can be compared with those derived from the photographic B survey of Smith et al. (1992). The $P-L$ relations from Smith et al. (1992) are:

$$\langle B \rangle_0 = -2.71(\pm 0.09) \log P_0 + 18.03(\pm 0.14) \,, \tag{17}$$

$$\langle B \rangle_0 = -2.98(\pm 0.17) \log P_1 + 17.35(\pm 0.14) \,, \tag{18}$$

for fundamental mode and first overtone mode Cepheids respectively. These differ from those in Table 9 in having steeper slopes and fainter zero-points.

At $\log P = 0.8$, near $B = 15.8$, the difference between the CCD and photographic $P - L$ relations for fundamental mode Cepheids is about 0.1 mag. At $\log P = 0.2$, near $B = 17.3$, the $P - L$ relation derived from the CCD data is about 0.22 mag brighter than that obtained by Smith et al. (1992). Of these differences, 0.04 mag is accounted for by the different adopted reddening values in the two studies. In addition, the mean magnitudes given in Smith et al. (1992) are magnitude averages, rather than the luminosity-weighted magnitudes used here. The effect which this has depends upon the lightcurve shape of the variable under consideration. For a typical fundamental mode Cepheid, the luminosity-weighted magnitudes will be about 0.08 mag brighter than those obtained from averaging magnitudes. These two differences account for essentially all of the discrepancy in the two $P - L$ relations near $\log P = 0.8$. Together, however, they account for only about half of the discrepancy near $\log P = 0.2$.

As will be discussed below, there may be a break in the slope of the $P - L$ relation near a period of 2 days for fundamental mode Cepheids. This break was not noted in Smith et al. (1992), although there is some evidence for its existence in their $P - L$ relation. There are different numbers of Cepheids with periods longer and shorter than two days in the present study as compared to Smith et al. (1992). The stars of period smaller than the break thus enter with somewhat different weight into the calculation of the photographic and CCD $P - L$ relations. This is responsible for a portion of the remaining discrepancy at fainter magnitudes. Nonetheless, comparison of stars common to the two studies suggests that, at $B \sim 17$, there is a systematic difference of about 0.05 mag between the photographic and CCD magnitude systems, with the latter being the brighter. We note that there is some evidence for a field dependent magnitude error of about 0.1 mag in the photographic photometry (Smith et al. 1992; Graham 1975), so that this zero-point shift may not perfectly apply across the entire photographic field.

The comparison of the B $P - L$ relations for the first overtone Cepheids is more complicated, being influenced by the inclusion in this study of significant numbers of variables not discovered in the earlier photographic survey. Part of the difference between the photographic and CCD $P - L$ relations appears to be attributable to this. Again, however, comparison of the lightcurves of individual variables indicates a systematic difference of 0.05 mag at $B \sim 17$, in the sense that the CCD photometry is brighter.

Caputo et al. (2000) predict that, at Z = 0.004, the slope of the B $P - L$ relation will be -2.49, for all fundamental mode Cepheids, and -2.71, if limited to only those Cepheids having $\log P_0 < 1.5$. For V, the corresponding theoretical slopes in Caputo et al. (2000) are -2.60

and -2.94. The Cepheids in this study have periods less than $\log P_0 = 1.5$, but the $P - L$ relation slopes listed in Table 9 are slightly less steep than those predicted for such stars. As shown in Figure 16, a quadratic fit to the V $P - L$ relation describes our data better than a single linear $P - L$ relations. However, because relatively few longer period Cepheids are included in our sample, it is not possible to make a meaningful quantitative comparison with the theoretical second order $P - L$ relationships given in Caputo et al. (2000). The theoretical Wesenheit relation for fundamental mode Cepheids in Table 7 of Caputo et al. (2000) has a slope of -3.65 $\pm$ 0.02, which is very close to the observed value of -3.63 $\pm$ 0.12 in Table 10.

The EROS group (Bauer et al. 1999) reported the existence of a change in the slope of the $P - L$ relation for fundamental mode Cepheids at periods shorter than 2 days. This steepening of the $P - L$ slope was also noted by the OGLE II group (Udalski et al. 1999a). Our sample size is smaller than those of the EROS and OGLE II studies, making the recognition of a change in slope difficult. Nevertheless, when our population of fundamental mode Cepheids is divided at a period of 2 days, it is evident that the two samples possess distinctly different slopes. This is shown graphically in Figures 17 and 18, and coefficients for the resultant fits are listed in Table 11.

Bauer et al. (1999) note that a similar shift is not clearly seen in the $P - L$ relation of the first overtone Cepheids. To demonstrate this they divide their first overtone population into samples at $P = 1.4$ days, the period of a first overtone Cepheid which would correspond to a 2 day fundamental mode period. Although some steepening of their $P - L$ relationship for first overtone mode Cepheids was present at periods shorter than 1.4 day, the change in slope at that period was not statistically significant.

In Table 11 we list the coefficients we obtain fitting $P - L$ relations to our sample of first overtone mode Cepheids, considering separately those with periods longer and shorter than 1.4 day. The overtone slopes, while they do show a tendency to steepen below a period of 1.4 days, do not demonstrate as significant a difference as is evident for the fundamental mode pulsators. The difference in the coefficients of the slope for periods above and below 1.4 days falls within the limits expected from the uncertainties of the coefficients. This is consistent with the findings of Bauer et al. (1999).

Bauer et al. (1999) considered four possible explanations for the change in the $P - L$ slope of the fundamental mode Cepheids: superposition of two Cepheid populations of different ages and distances, mixing of classical Cepheids and anomalous Cepheids, non-uniform filling of the instability strip, and a thinning of the instability strip at short periods. Smith et al. (1992) had also noted the possibility that some of the shorter period fundamental mode Cepheids might actually be anomalous Cepheids.

Bauer et al. (1999) found no clear evidence for the superposition hypothesis, particularly since they detected no significant change in the $P - L$ slope for the shortest period first overtone Cepheids. They further argued that the faint Cepheids were unlikely to be anomalous Cepheids of the sort present in dwarf spheroidal systems because a known metallicity dependence of the anomalous Cepheid $P - L$ relation (Nemec et al. 1994) would require metallicities much lower than are thought to be common in the stellar population of the SMC. We note, however, that the dependence of the anomalous Cepheid $P - L$ relation upon metallicity found by Nemec et al. (1994) is tied to an adopted metallicity-luminosity relation for RR Lyrae stars. The slopes of the anomalous Cepheid $P - L$ relations in Nemec et al. (1994) are, however, shallower than those reported in Table 11 for fundamental mode Cepheids with periods smaller than 2 days, which is an argument against the anomalous Cepheid hypothesis.

There is some theoretical support for the idea that the lower end of the Cepheid instability strip might not be completely filled. Cepheids cross into the instability strip during the blue-loop phase of their evolution, with the extent of the loop increasing with mass. Low mass fundamental mode Cepheids are reasoned not to have as broad an excursion into the instability strip, indeed eventually missing portions of the strip, then missing the entire strip as the mass continues to decrease. The result is a truncation of the portion of the instability strip that can be physically occupied by stars pulsating in the fundamental mode. This decreases the "width" of the observed instability strip for fundamental mode Cepheids, with a consequent shift in the $P - L$ relation. The models of Baraffe et al. (1998) and Alibert et al. (1999) show that such an effect can produce a change in the slope of the $P - L$ relation.

This hypothesis suffers from the lack of a similar observed change in the first overtone $P - L$ relation, as noted by Bauer et al. (1999). The region of the instability strip occupied by first overtone pulsators is bluer than that occupied by the fundamental mode pulsators. Stars with blue-loops unable to extend into the fundamental portion of the strip ought not to be able to extend into the overtone portion of the strip either. The result would be a depopulation of the overtone sequence at a period corresponding to the luminosity at which the effect is first noticed in the fundamental sequence. A period of 2 days for the fundamental mode Cepheids would translate to the aforementioned 1.4 days for overtone mode Cepheids. Thus, were this explanation correct, we would expect the first overtone sequences to be depopulated at periods shorter than 1.4 days. While the EROS photometry (Bauer et al. 1999), our photometry, and the OGLE II photometry (Udalski et al. 1999b) all indicate that there may be some steepening of the $P - L$ slope for short period first overtone Cepheids, in each case the effect is of doubtful statistical significance. Moreover, relatively large numbers of first overtone mode Cepheids are present at periods shorter than 1.4 days.

Alibert et al. (1999) note that their models suggest that the change in slope of the first overtone $P - L$ relation might be less pronounced, due to a narrowing of the portion of the instability strip occupied by first overtone mode pulsators with respect to that portion in which fundamental mode pulsators reside. However, Alibert et al. (1999) further noted, though, that their models require that first overtone Cepheids in the SMC with periods shorter than one day should be in the first crossing of the instability strip. Because first crossing stars evolve quickly through the instability strip, they cannot explain the relatively large number of short period first overtone Cepheids which are actually observed, unless stars immersed in this phase of their evolution somehow preferentially pulsate in the first overtone mode.

Our color-magnitude data for SMC Cepheids, and those from Udalski et al. (1999b), do indicate that there may be some change either in the boundaries of the instability strip, or in the occupied region of the instability strip, at lower luminosities. Figures 7 and 8 show that the redward limit of the region occupied by fundamental mode pulsators shifts to bluer colors at $\langle V \rangle_0 \geq 17$. This shift is also noticeable as a slight bend at the very faint end of the period-color relation for fundamental mode Cepheids. The situation for the first overtone pulsators is less clear, particularly because of the redder first overtone pulsators seen in SC10 and SC11 but not within our field. If all else were equal, a blueward shift in the red boundary of the instability strip would tend to remove the longer period Cepheids from the sample at a given luminosity. By itself, this would not produce a shift in the right direction to explain the observed change in $P - L$ slope.

Udalski et al. (1999a) applied an iterative least squares fitting routine to fundamental mode Cepheids with periods above $\log P = 0.4$, a cutoff they selected to avoid the possible change in slope among the short period Cepheids. Their initial fit in V yielded a shallower slope (-2.57) for the V $P - L$ relation in the SMC compared to that derived from their LMC sample (-2.78). On the basis of the more numerous population of longer period ($\log P \geq 0.4$) fundamental mode Cepheids in the LMC, and the smaller scatter about the LMC V $P - L$ relation, Udalski et al. (1999a) decided to adopt the steeper LMC slope as the effective SMC slope, and consequently re-fitted their SMC data. In Table 12 we list both their original SMC fits, as well as the V fit obtained with the adopted, steeper LMC slope. The $P - L$ relations listed in Table 12 and previously quoted coefficients are those from the OGLE website, and so include the revisions made in 2000 (Udalski et al. 2000). A direct comparison between our relations and those from the EROS study (Bauer et al. 1999) was not made since they employ photometric bandpasses different than Johnson B and V.

The $P - L$ relations in Table 12 may be compared with those obtained for the fundamental mode Cepheids in our sample having periods longer than 2 days (Table 11). The

least squares fit to our sample gives a slope consistent with the Udalski et al. (1999a) original fit to their V data. However, the uncertainty is large enough to encompass the steeper slope of their adopted fit. The zero-points of the $P - L$ relations of our sample are, however, slightly smaller than those found by Udalski et al. (1999a). That is particularly so for their "adopted" fit, but is true to a lesser extent for their "original" fit.

9. Relative distance and depth of the northeast arm Cepheids

There has been some debate regarding the depth of the SMC along the line of sight and whether different regions of the SMC lie at different mean distances. Caldwell & Coulson (1986) used $BVRI$ observations of 63 Cepheids to conclude that we see the central bar of the SMC about edge on, and that it has a depth of about 10 kpc. They found the northeast arm to be nearer to us than the central bar, and the southwest region to be more distant, though with a superimposed nearer component. Mathewson et al. (1986) argued for a distance spread of some 30 kpc among SMC Cepheids, while Mathewson et al. (1988) used observations of 61 Cepheids to argue that the SMC as a whole has a depth of some 20 kpc. They interpreted their data as showing that the northeastern arm Cepheids were some 10-15 kpc closer than those in the southern section. However, they found the Cepheids in the northeastern arm to be only slightly nearer than those of the central bar. In contrast, Welch et al. (1987) concluded from infrared observations of SMC Cepheids that the depth of the SMC was smaller, and that the Cepheids generally fell within the circa 4 kpc tidal radius of the SMC.

Hatzidimitriou & Hawkins (1989) investigated the distribution of a different stellar population, using photometry of horizontal branch/red clump stars in outlying northeastern and southwestern regions to conclude that the older SMC population shows a relatively large line of sight depth. In their northeastern region, which is further from the central part of the SMC than our field, they found a line of sight depth of 17 kpc on average.

To provide further insight into this issue, we can compare the $P - L$ relations for our northeast arm field with those Udalski et al. (1999a) obtained for the main body of the SMC, and with those which may be derived from the Udalski et al. data for the more northeasterly of the fields covered in their survey.

We have constructed $P - L$ relations for Cepheids in OGLE II fields SC10 and SC11 (Udalski et al. 1999b, using updated photometry in Udalski et al. 2000) which, as we have noted earlier, are the OGLE II fields closest on the sky to our own. These $P - L$ relations are listed in Table 13 and depicted in Figures 19 through 22. For the fits to the fundamental

mode Cepheids, the slopes of the SC10–11 $P - L$ relations are steeper than those obtained for our northeast arm field and the zero points are about 0.08 or 0.09 magnitudes fainter than those which we obtained (Table 9), but the differences are significant only at the one sigma level. At $\log P = 0.4$, the $P - L$ relations for our fundamental mode Cepheids predict B and V magnitudes which are brighter by 0.04 mag or less than those predicted by the $P - L$ relations derived for the Cepheids in SC10 and SC11. The $P - L$ relations for the first overtone mode Cepheids are somewhat more discrepant, but this is mainly attributable to the faint, redder first overtone Cepheids which, as we have noted, seem to be present in SC10 and SC11, but not within our field. We conclude that our northeast arm Cepheids can be at most only slightly closer than those in SC10 and SC11; i.e. there is no steep gradient in mean distance in going along the northeast arm from the SC10 and SC11 fields to our more outlying field.

The scatter about the mean $P - L$ relation for each field is contributed by at least three separate effects: observational uncertainty (including blending of images and differential reddening), the finite color width of the $P - L$ relation, and the geometric depth of the SMC in the region under consideration. The scatter of the individual Cepheids about the mean $P - L$ relation is smaller for our dataset ($\sigma = 0.20$ in V) than for the SC10 and SC11 dataset ($\sigma = 0.24$). However, it is unclear whether this signifies a genuine difference between these fields. The northeast arm field is less crowded than SC10 and SC11, on average, and in deriving its $P - L$ relation we included only Cepheids with good lightcurves.

Correcting for the observed width of the Cepheid domain in the color-magnitude diagram (see Figure 7), the residual scatter of the northeast arm Cepheids about the $P - L$ relations is about $\sigma = 0.15$, when results from both fundamental mode and first overtone mode Cepheids are combined. Taken at face value, this corresponds to a depth along the line of sight of $\pm$ 4 kpc. There are, of course, outliers for which a distance greater than 4 kpc from the mean would be determined, but it is also true that some of the deduced range in distance is actually attributable to observational error rather than a true distance spread. It is difficult to decide therefore the extremes in distance of the Cepheids in the northeast arm field. It is clear, however, that most Cepheids within this field are located within $\pm$ 4 kpc of the mean distance, and that a very large proportion are located within $\pm$ 6 kpc.

The differences between our $P - L$ relations for the northeast arm field and those derived by Udalski et al. (1999a) from their entire SMC Cepheid dataset are somewhat greater. The least squares fit to the V data for our longer period fundamental mode Cepheids (Table 11), predicts $\langle V \rangle_0 = 16.33 \pm 0.07$ at $\log P = 0.4$, whereas Udalski et al.'s (1999a, 2000) original fit to the full OGLE II dataset (Table 12) predicts $\langle V \rangle_0 = 16.46 \pm 0.02$, and their adopted fit gives $\langle V \rangle_0 = 16.53$. The corresponding predictions in the B passband are $\langle B \rangle_0 = 16.78$

$\pm$ 0.09 for our fit, and 16.84 $\pm$ 0.03 for the original fit of Udalski et al. (1999a, 2000). The differences for the first overtone $P - L$ relations are larger, but, as noted earlier, they are more difficult to interpret because of the apparent presence of some types of first overtone Cepheids in the OGLE II fields not found within our northeast arm field.

Considering the respective uncertainties, these differences must be regarded as of marginal significance. Nonetheless, they are consistent with the northeast arm being closer than the main body of the SMC by about 4 kpc. The smaller scatter of the observations about the mean $P - L$ relation for our northeast arm Cepheids compared to the entire OGLE II dataset is consistent with the existence of a greater dispersion in distances among the entire OGLE II Cepheid population than among the Cepheids of the northeast arm. However, because the entire OGLE II sample also includes some Cepheids which suffer significant problems with crowding, photometric errors may also contribute to that increased scatter.

10. RR Lyrae Stars

Two groups of RR Lyrae variables are apparent in Figure 4. Foreground field RR Lyrae stars have the periods and lightcurve shapes typical of RR Lyrae stars, but their mean magnitudes scatter between 15 and 18. Then there are the actual SMC RR Lyrae stars, clustered at $V \geq 19$. The survey of SMC RR Lyrae stars within our field is very incomplete, and their lightcurves are fairly noisy. Even those SMC RR Lyrae labeled as having quality "1" lightcurves in Table 6 have poorer quality lightcurves than quality "1" SMC Cepheids (but better lightcurves than the SMC RR Lyrae labeled quality "2"). The seven RRab stars in the SMC with quality "1" V lightcurves have $\langle V \rangle = 19.39 \pm 0.06$. The five RRab stars with relatively good B lightcurves have $\langle B \rangle = 19.74 \pm 0.08$. These values are likely to be biased because the RR Lyrae with the better lightcurves also tend to be among the brighter SMC RR Lyrae in the sample. The mean value of the luminosity-weighted $\langle V \rangle$ values for 11 probable SMC RR Lyrae stars (including some with poorer lightcurves) is 19.43 ± 0.05. The luminosity-weighted mean magnitude for the 9 SMC RR Lyrae with usable values of $\langle B \rangle$ is 19.78 ± 0.06. Smith et al. (1992) found a range in $\langle B \rangle$ among the RR Lyrae stars of the northeast arm of the SMC, with a mean magnitude weighted B of 19.88 ± 0.04. The corresponding magnitude weighted mean B magnitude for the present study is 19.83 ± 0.05, in good agreement considering the uncertainties, even though the search for RR Lyrae stars in the present study is more incomplete than in the earlier photographic survey.

Our mean magnitudes for the RR Lyrae stars in the northeast arm field are slightly brighter than the intensity weighted averages Walker & Mack (1988) found for RR Lyrae stars in the SMC cluster NGC 121, $\langle V \rangle = 19.58$ and $\langle B \rangle = 19.91$, or Graham's (1975) values

for RR Lyrae stars in the field around NGC 121, $\langle V \rangle = 19.57$ and $\langle B \rangle = 19.95$. It is difficult to state to what degree the incompleteness of the RR Lyrae sample in the present survey is responsible for the difference. However, because of the possibility that our survey is biased toward the brighter RR Lyrae stars, the differences with the Graham and Walker & Mack studies cannot be regarded as evidence that the RR Lyrae population in our northeast arm field is nearer than that around NGC 121.

11. Conclusions

We observe a Cepheid population in the northeast arm which is in most respects indistinguishable from that seen in prior studies of other regions of the SMC. The absence of the faint, redder first overtone Cepheids found in SC10 and SC11 is a possible exception to that conclusion. To within the uncertainties, the slopes of the period-luminosity relations we derive for the northeast arm field are identical to those which have been obtained for more central regions of the SMC. The northeast arm Cepheids may be slightly nearer on average than the Cepheids in the main body of the SMC, but the difference is no greater than about 4 kpc. The Cepheids in the northeast arm region covered by our observations are, at most, only slightly nearer than those in OGLE II fields SC10 and SC11, which lie between our field and the central area of the SMC.

Although the number of faint fundamental mode Cepheids within our sample is relatively small, our data support the existence of a break in the slope of the $P - L$ relation for fundamental mode Cepheids at periods shorter than 2 days. There is evidence for a similar break in the $P - L$ relation for the first overtone mode Cepheids near a period of 1.4 days, but in this case the evidence for the break is not statistically significant. The independent EROS and OGLE II studies also found marginal evidence for such a break in the slope of the first overtone $P - L$ relation, which strengthens the case for its reality, but not conclusively.

The first overtone mode and fundamental mode Cepheids occupy distinct regions of the $V, (B - V)$ CMD. There is some overlap between the fundamental mode and first overtone mode Cepheid regions in the CMD, but this overlap can in most cases be attributed to the observational uncertainty of the photometry. In the few cases in which the overlap in color is too large to be explained in this fashion, the existence of a few instances of unresolved red or blue companions to the Cepheids provides a satisfactory alternative. Below $\langle V \rangle = 17$, the red edge of the region of the CMD occupied by fundamental mode pulsators shifts to bluer colors. This shift does not, by itself, provide an explanation for the break in the slope of the $P - L$ relation at $P = 2$ days.

The period-color relations we obtain are in excellent agreement with those found in analyses of Cepheids in the OGLE II survey. However, the observed period-color relation for fundamental mode Cepheids is significantly bluer than the theoretical period-color relation of Alibert et al. (1999) and is slightly bluer than that of Caputo et al. (2000).

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Fig. 1a.— Finding chart for newly discovered variable stars (SSP numbers) in the northwest quadrant (field 1). East is at the bottom and north is at the left.

Fig. 1b.— Finding chart for newly discovered variable stars (SSP numbers) in the northeast quadrant (field 2). East is at the bottom and north is at the left.

Fig. 1c.— Finding chart for newly discovered variable stars (SSP numbers) in the southeast quadrant (field 3). East is at the bottom and north is at the left.

Fig. 1d.— Finding chart for newly discovered variable stars (SSP numbers) in the southwest quadrant (field 4). East is at the bottom and north is at the left.

Fig. 2.— Finding chart for the local photometric standards. North is at the bottom and east is at the left.

Fig. 3.— B and V light curves for variable stars within the northeast arm field. Variables observed in both B and V are shown first. Variables observed in only a single band are included at the end of the figure.

Fig. 4.— Pulsating variable stars with quality "1"(see Table 6) light curves in both B and V in the $\langle V \rangle$ versus $\log P$ diagram. Fundamental mode Cepheids, first overtone mode Cepheids, and RR Lyrae stars are identified.

Fig. 5.— Histograms over period for fundamental mode and first overtone mode Cepheids reported in this paper and in Smith et al. (1992)

Fig. 6.— Histograms over period for quality "1" Cepheids and for all Cepheids reported in this paper.

Fig. 7.— $\langle V \rangle_o - (B-V)_{mag,o}$ Color-magnitude diagram for fundamental mode (filled triangles) and first overtone mode (open circles) Cepheids in the northeast arm. Only those stars with quality "1" light curves in both B and V are included.

Fig. 8.— Same as Figure 7, but including fundamental mode (filled squares) and first overtone mode (open squares) Cepheids from fields SC10 and SC11 of Udalski et al. (1999b).

Fig. 9.— Period-color relations for fundamental mode Cepheids. Shown are least squares fits to our Cepheids with quality colors and to the OGLE II dataset (Udalski et al. 1999b), as well as the theoretical period-color relations of Alibert et al. (1999) and Caputo et al. (2000). The former two overlap.

Fig. 10.— Period-color relations for first overtone mode Cepheids. Least squares fits to our Cepheids with quality colors and to the OGLE II dataset (Udalski et al. 1999b) are shown.

Fig. 11.— B period-luminosity relation for fundamental mode Cepheids in the northeast arm field. Least squares and least absolute deviation fits are shown.

Fig. 12.— B period-luminosity relation for first overtone mode Cepheids in the northeast arm field. The overlapping least squares and least absolute deviation fits are shown.

Fig. 13.— V period-luminosity relation for fundamental mode Cepheids in the northeast arm field. The overlapping least squares and least absolute deviation fits are shown.

Fig. 14.— V period-luminosity relation for first overtone mode Cepheids in the northeast arm field. The overlapping least squares and least absolute deviation fits are shown.

Fig. 15.— Reddening insensitive W_{BFM} versus $\log P$ relations for northeast arm Cepheids. Least squares fits shown.

Fig. 16.— Second order fit to the V period-luminosity relation for fundamental mode Cepheids.

Fig. 17.— Change in slope of the B period-luminosity relation for fundamental mode Cepheids at $P = 2$ days. Least squares and least absolute deviation fits are shown.

Fig. 18.— Change in slope of the V period-luminosity relation for fundamental mode Cepheids at $P = 2$ days. Least squares and least absolute deviation fits are shown.

Fig. 19.— B period-luminosity relation for fundamental mode Cepheids in OGLE II fields SC10 and SC11 (Udalski et al. 1999b). Our linear least squares fit to the SC10 and SC11 data is shown, as is the least squares fit to our northeast arm sample.

Fig. 20.— V period-luminosity relation for fundamental mode Cepheids in OGLE II fields SC10 and SC11. Fits shown are the same as in Figure 19.

Fig. 21.— B period-luminosity relation for first overtone mode Cepheids in OGLE II fields SC10 and SC11. Fits shown are the same as in Figure 19.

Fig. 22.— V period-luminosity relation for first overtone mode Cepheids in OGLE II fields SC10 and SC11. Fits shown are the same as in Figure 19.

Table 1.   Journal of Observations

Heliocentric Julian Dates	Year	Months
2448888 - 2448890	1992	September
2448924 - 2448926	1992	October
2449250 - 2449253	1993	September
2449301 - 2449304	1993	November
2449652 - 2449656	1994	October

Table 2. Coordinates of New Variables

SSP	RA (J2000)	DEC (J2000)
1	0:57:08.6	-71:40:06
2	0:57:15.1	-71:49:26
3	0:57:15.9	-71:50:33
4	0:57:27.5	-71:40:57
5	0:57:54.7	-71:40:52
6	0:57:58.7	-71:36:37
7	0:58:02.5	-71:24:57
8	0:58:13.4	-71:26:55
9	0:58:17.2	-71:51:54
10	0:58:24.7	-71:42:38
11	0:58:33.5	-71:34:46
12	0:58:43.3	-71:42:38
13	0:58:53.7	-71:49:28
14	0:58:55.1	-71:39:03
15	0:59:12.9	-71:48:13
16	0:59:13.4	-71:34:46
17	0:59:16.4	-71:43:30
18	0:59:31.5	-71:51:40
19	0:59:35.4	-71:17:44
20	1:00:02.3	-71:42:08
21	1:00:36.1	-71:47:30
22	1:00:54.3	-71:44:44
23	1:00:56.4	-71:01:42
24	1:00:59.8	-71:12:59
25	1:01:10.1	-71:28:12
26	1:01:16.8	-71:48:41
27	1:01:43.4	-71:25:34
28	1:01:56.7	-71:16:31
29	1:01:56.8	-71:10:00
30	1:02:21.6	-71:29:49
31	1:02:32.1	-71:44:00

Table 2—Continued

SSP	RA (J2000)	DEC (J2000)
32	1:02:42.6	-71:08:22
33	1:02:46.1	-71:32:19
34	1:02:50.8	-71:43:45
35	1:03:04.4	-71:34:39
36	1:03:14.9	-71:44:53
37	1:03:23.2	-71:11:42
38	1:03:48.3	-71:22:12
39	1:03:49.9	-71:24:40
40	1:03:51.1	-71:42:02
41	1:04:09.9	-71:23:51
42	1:04:20.5	-71:40:38
43	1:04:21.8	-71:46:03
44	1:04:28.7	-71:04:19
45	1:04:32.9	-71:41:24
46	1:04:38.2	-71:40:08
47	1:04:39.6	-71:47:16
48	1:04:45.1	-71:53:41
49	1:04:52.2	-71:25:20
50	1:05:01.2	-71:43:34
51	1:05:07.6	-71:44:33
52	1:05:28.1	-71:40:11
53	1:05:39.4	-71:29:13
54	1:05:49.7	-71:46:56
55	1:06:02.2	-71:41:02
56	1:06:08.5	-71:49:18
57	1:06:18.4	-71:41:43
58	1:06:30.0	-71:08:04
59	1:06:44.3	-71:42:12
60	1:06:49.0	-71:29:22
61	1:06:51.3	-71:53:29
62	1:06:53.3	-71:37:05

Table 2—Continued

SSP	RA (J2000)	DEC (J2000)
63	1:06:59.1	-71:41:06
64	1:07:03.5	-71:39:15
65	1:07:22.8	-70:53:14
66	1:07:42.2	-71:42:56
67	1:07:43.4	-71:13:21
68	1:07:50.6	-71:33:03
69	1:07:52.7	-71:14:13
70	1:07:53.9	-71:50:18
71	1:08:07.4	-71:11:42
72	1:08:08.7	-71:17:24
73	1:08:27.7	-70:53:06
74	1:08:32.9	-71:29:13
75	1:08:50.3	-71:22:33
76	1:08:59.8	-71:34:14
77	1:09:00.0	-71:52:14
78	1:09:02.8	-70:55:13
79	1:09:09.3	-71:19:34
80	1:09:10.2	-71:30:28
81	1:09:13.7	-70:53:33
82	1:09:15.6	-70:55:28
83	1:09:22.6	-71:14:39
84	1:09:25.0	-71:18:11

Table 3.   Photometry of Local Standard Stars

ID	RA (J2000)	DEC (J2000)	V	$B-V$	$U-B$	$V-I$
A	1:05:59.9	-71:26:11	13.173	0.628	$\cdots$	0.714
			13.176	0.627	0.098	0.716
B	1:04:43.2	-71:25:56	12.706	0.770	$\cdots$	0.819
			12.706	0.774	0.386	0.817
C	1:05:53.4	-71:22:39	14.074	0.760	$\cdots$	0.869
			14.073	0.755	0.199	0.865
			14.082	0.744	0.188	0.874
D	1:05:57.8	-71:19:14	12.456	0.040	$\cdots$	0.114
			12.457	0.040	-0.121	0.116
E	1:06:08.9	-71:17:08	13.817	0.746	0.394	0.773
			13.821	0.742	$\cdots$	0.771
			13.825	0.740	0.377	0.778
F	1:05:06.6	-71:18:06	13.422	0.643	0.180	0.698
			13.435	0.651	$\cdots$	0.691
G	1:04:41.6	-71:16:46	12.880	0.426	$\cdots$	0.540
			12.879	0.422	-0.096	0.539
H	1:04:10.0	-71:17:13	14.833	0.688	0.178	0.727
			14.852	0.675	$\cdots$	0.755
			14.846	0.679	0.171	0.742
I	1:03:53.8	-71:18:54	15.076	-0.240	-0.931	-0.247
			15.070	-0.237	$\cdots$	-0.263
			15.066	-0.233	-0.947	-0.266
J	1:04:44.3	-71:20:29	15.939	0.599	$\cdots$	0.734
			15.934	0.613	0.071	0.710
			15.951	0.606	0.051	0.745
K	1:04:53.3	-71:19:59	15.331	0.757	0.318	0.828
			15.335	0.760	$\cdots$	0.835
			15.330	0.763	0.325	0.826
L	1:05:51.7	-71:18:16	14.807	0.711	0.203	0.822
			14.800	0.719	0.214	0.821
			14.805	0.714	$\cdots$	0.818

Table 3—Continued

ID	RA (J2000)	DEC (J2000)	V	$B - V$	$U - B$	$V - I$
M	1:04:13.5	-71:25:16	15.092	0.836	0.386	0.986
			15.087	0.824	$\cdots$	0.962
			15.077	0.830	0.360	0.951
N	1:04:42.3	-71:25:08	15.754	-0.225	-0.894	-0.255
			15.744	-0.218	-0.871	-0.256
			15.754	-0.220	$\cdots$	-0.238
O	1:05:56.2	-71:20:25	16.829	1.486	0.621	1.443
			16.830	1.522	$\cdots$	1.421
			16.852	1.509	2.516	1.462
P	1:05:10.5	-71:19:04	16.497	1.230	$\cdots$	1.300
			16.483	1.244	0.898	1.298
			16.483	1.219	0.949	1.282
Q	1:05:16.1	-71:19:22	16.722	0.969	0.545	1.027
			16.749	0.967	$\cdots$	1.052
			16.747	0.933	0.430	1.029
R	1:04:52.0	-71:25:39	16.909	0.967	$\cdots$	1.062
			16.885	0.943	0.690	1.045
			16.891	0.959	0.480	1.071
S	1:04:04.7	-71:28:23	16.853	0.557	$\cdots$	0.824
			16.846	0.551	-0.011	0.716
			16.825	0.555	0.127	0.774
T	1:04:05.3	-71:27:37	15.641	0.689	0.237	0.727
			15.646	0.686	$\cdots$	0.758
			15.640	0.686	0.211	0.751
U	1:05:31.4	-71:21:32	15.688	0.026	$\cdots$	0.022
			15.690	0.033	-0.065	0.025
			15.689	0.027	-0.038	0.026

Table 4. Comparison of Photometry

Reference	n	ΔV	ΔB
Harris	12	0.021 ± 0.010	0.013 ± 0.014
Da Costa et al.	4	$\cdots$	-0.003 ± 0.021

Table 5.   Photometry of Individual Variable Stars

Star ID	Field	Bandpass	HJD	Mag	Error
HV214	2	B	2448889.6461	16.588	0.007
HV214	2	B	2448889.7790	16.597	0.007
HV214	2	B	2448890.6559	16.797	0.008
HV214	2	B	2448890.7980	16.811	0.007
HV214	2	B	2448924.5873	16.848	0.009
HV214	2	B	2448924.8235	16.790	0.009
HV214	2	B	2448925.5839	15.451	0.004
HV214	2	B	2448925.7343	15.535	0.004
HV214	2	B	2448926.5962	16.156	0.006
HV214	2	B	2448926.7483	16.242	0.006
HV214	2	B	2449252.7222	17.056	0.008
HV214	2	B	2449253.6185	15.305	0.003
HV214	2	B	2449253.7711	15.538	0.003
HV214	2	B	2449301.5958	16.553	0.005
HV214	2	B	2449301.7486	16.560	0.006
HV214	2	B	2449302.6621	16.798	0.007
HV214	2	B	2449303.6598	15.969	0.004
HV214	2	B	2449304.6476	15.890	0.004
HV214	2	B	2449304.8149	15.993	0.004
HV214	2	B	2449653.5560	15.846	0.004
HV214	2	B	2449653.7614	15.960	0.005
HV214	2	B	2449656.6026	16.839	0.008
HV214	2	V	2448888.6283	15.767	0.005
HV214	2	V	2448888.7495	15.691	0.005
HV214	2	V	2448888.8414	15.781	0.005
HV214	2	V	2448889.6633	16.003	0.004
HV214	2	V	2448889.7967	16.038	0.005
HV214	2	V	2448890.6714	16.154	0.005
HV214	2	V	2448924.6517	16.212	0.005
HV214	2	V	2448924.8426	16.301	0.008
HV214	2	V	2448925.5980	15.154	0.003

Table 5—Continued

Star ID	Field	Bandpass	HJD	Mag	Error
HV214	2	V	2448925.7532	15.266	0.003
HV214	2	V	2448926.5716	15.846	0.005
HV214	2	V	2448926.7215	15.791	0.004
HV214	2	V	2449253.6007	14.985	0.003
HV214	2	V	2449253.7889	15.220	0.003
HV214	2	V	2449301.6124	15.965	0.004
HV214	2	V	2449302.6453	16.201	0.006
HV214	2	V	2449302.7927	16.199	0.005
HV214	2	V	2449303.6426	15.652	0.004
HV214	2	V	2449303.7860	15.345	0.003
HV214	2	V	2449304.7977	15.585	0.004
HV214	2	V	2449652.7206	15.533	0.005
HV214	2	V	2449653.5739	15.451	0.004
HV214	2	V	2449653.7438	15.533	0.004
HV214	2	V	2449656.6205	16.138	0.005

Note. — The complete version of this table is in the electronic edition of the Journal. The printed edition contains only a sample.

Table 6.   Attributes of Observed Variables

Num	Type	P (days)	$\langle B \rangle$	$\langle V \rangle$	$\langle B \rangle - \langle V \rangle$	$(B-V)_{mag}$	Qual	Notes
HV								
214	F	4.20494	16.232	15.775	0.457	0.498	2	
841	F	1.90951	17.010	16.696	0.314	0.347	1	
856	F	6.07682	15.936	15.139	0.797	0.810	2	
1717	F	1.87023	17.117	16.766	0.351	0.394	1	
1718	F	4.04534	16.439	15.954	0.485	0.497	2	
1727	F	2.22099	16.636	16.362	0.274	0.300	1(V)	
1732	F	1.75459	17.158	16.844	0.314	0.323	1(V)	
1755	O	1.50575	16.837	16.525	0.312	0.322	1	
1759	F	1.73444	17.156	16.758	0.398	0.404	1	
1779	O	1.78335	16.532	16.144	0.388	0.398	1	
1788	O	3.47885	15.762	15.338	0.424	0.428	1	
1793	F	4.18158	16.549	16.021	0.528	0.558	2	
1807	F	4.08858	16.569	16.067	0.502	0.523	2	
1855	F	6.83922	15.922	15.361	0.561	0.579	1	
1860	O	1.98478	16.345	16.001	0.344	0.349	1	
1863	RRab	0.51327	18.162	17.733	0.429	0.430	2	[a]
1869	F	2.46485	17.381	16.849	0.532	0.541	1	
1871	F	1.30090	17.515	17.175	0.340	0.380	1	
1883	O	2.01315	16.536	16.102	0.434	0.444	1	
1890	F	1.77851	17.215	16.825	0.390	0.428	1	
1892	F	5.65497	16.292	15.700	0.592	0.601	2	
1897	O	1.24131	17.089	16.738	0.351	0.360	1(V)	
1898	F	3.01818	16.434	16.141	0.293	0.296	2	[b]
1901	F	3.57357	16.900	16.323	0.577	0.591	1	
1906	F	3.06560	16.759	16.230	0.529	0.551	2	
1907	F	1.64318	17.243	16.873	0.370	0.420	1(B)	
1919	F	1.71874	17.501	17.071	0.430	0.478	1	
1929	F	5.58692	15.958	15.520	0.438	0.442	1	
1934	F	4.87545	16.294	15.758	0.536	0.560	1	
1945	F	6.47378	15.936	15.382	0.554	0.579	1	

Table 6—Continued

Num	Type	P (days)	$\langle B \rangle$	$\langle V \rangle$	$\langle B \rangle - \langle V \rangle$	$(B - V)_{mag}$	Qual	Notes
1950	F	7.98574	15.752	15.108	0.644	0.655	1(B)	
1958	F	1.33443	17.653	17.256	0.397	0.460	1	
1970	F	3.33609	16.630	16.195	0.435	0.484	1(V)	
1976	F	1.90304	17.386	17.018	0.368	0.425	1(B)	
1982	F	5.22421	16.259	15.659	0.600	0.618	2	
1983	F	3.43840	16.255	15.824	0.431	0.459	1	
1987	F	3.13062	16.671	16.167	0.504	0.522	1	
1989	O	1.08200	17.014	16.627	0.387	0.398	1	
1999	F	1.96777	17.351	16.905	0.446	0.468	1	
2002	F	2.34646	16.966	16.543	0.423	0.477	1	
2003	F	5.05307	16.571	15.932	0.639	0.646	1	
2013	F	2.85747	16.756	16.321	0.435	0.486	1	
2014	F	2.20378	16.803	16.412	0.391	0.445	1	
2015	F	2.87409	17.091	16.549	0.542	0.565	1	
2017	F	11.40440	15.457	14.749	0.708	0.718	2	
2043	RRab	0.60337	15.593	15.220	0.373	0.389	1	
2045	F	2.84686	16.827	16.284	0.543	0.574	1	
2053	F	3.21897	16.805	16.332	0.473	0.499	1	
2054	F	7.16373	15.799	15.212	0.587	0.597	2	
2055	F	3.54469	16.974	16.363	0.611	0.615	2	
2057	F	1.90899	17.202	16.809	0.393	0.447	1	
2059	F	2.85985	16.739	16.328	0.411	0.422	1(V)	
2063	F	11.17360	15.425	14.777	0.648	0.672	2	
2068	O	1.80701	16.863	16.438	0.425	0.436	1	
2074	O	2.19972	16.487	16.120	0.367	0.378	1	
2076	F	2.49908	16.706	16.269	0.437	0.487	1	
2078	F	4.70610	16.330	15.801	0.529	0.559	1	
2085	F	3.71630	16.837	16.287	0.550	0.568	1	
2088	F	14.57880	15.533	14.754	0.779	0.807	2	
2102	RRab	0.51404	16.162	15.863	0.299	0.339	1	
2107	F	2.41154	16.885	16.439	0.446	0.482	1	

Table 6—Continued

Num	Type	P (days)	$\langle B \rangle$	$\langle V \rangle$	$\langle B \rangle - \langle V \rangle$	$(B - V)_{mag}$	Qual	Notes
10364	F	1.50304	17.870	17.238	0.632	0.683	1(V)	
10365	O	1.25811	17.202	16.840	0.362	0.377	1	
10367-1	F	1.54812	17.488	17.109	0.379	0.427	1	
10367-2	F	2.76831	17.194	16.680	0.514	0.531	1	
10373	F	3.07538	16.940	16.362	0.578	0.627	2	
10375	F	5.94034	16.402	15.783	0.619	0.625	1	
11190	O	1.36617	17.030	16.670	0.360	0.370	1(B)	
11191	F	1.96643	16.904	16.497	0.407	0.445	1	
11192	F	2.35403	16.964	16.570	0.394	0.423	2	
11197	F?	1.07507	17.109	16.713	0.396	0.409	2	
11199	F	2.09523	17.266	16.874	0.392	0.408	1	
11206	F	3.39809	16.691	16.195	0.496	0.507	1	
11209	O	1.92843	16.641	16.238	0.403	0.413	1	
11375	O	1.11490	17.134	$\cdots$	$\cdots$	$\cdots$	1	
11395	F	1.29710	18.081	17.621	0.460	0.478	1	
11449	O	1.31566	17.057	16.686	0.371	0.377	1	
11457	O	2.27465	16.619	16.234	0.385	0.391	1	
11463	F	1.75536	17.625	17.176	0.449	0.473	1	
11485	F	1.20924	17.829	17.449	0.380	0.421	1	
11500	O	1.78969	16.620	16.244	0.376	0.385	1	
11501	F	3.57905	16.914	16.306	0.608	0.614	2	
11502	?	3.27030	16.410	15.941	0.469	0.473	2	[c]
12942	F	3.89314	16.426	15.890	0.536	0.554	2	
12943	F	3.71538	16.643	16.090	0.553	0.572	1	
12949	RRab	0.47498	17.592	17.286	0.306	0.353	1	
13020	O	0.98915	17.424	17.111	0.313	0.326	2	
13021	O	1.81468	16.734	16.320	0.414	0.420	1	
NGC362V								
3	RRab	0.47324	15.836	15.533	0.303	0.356	1	
8	F	3.86046	16.355	15.896	0.459	0.514	1(B)	
[SSB92]								

Table 6—Continued

Num	Type	P (days)	$\langle B \rangle$	$\langle V \rangle$	$\langle B \rangle - \langle V \rangle$	$(B-V)_{mag}$	Qual	Notes
4	O	1.59263	17.114	16.649	0.465	0.478	1	
5	F	2.50085	17.144	16.657	0.487	0.509	1	
6	RRab	0.60537	19.689	19.240	0.449	0.474	2	
7	F	1.02203	18.130	17.751	0.379	0.394	2	
9	RRab	0.58500	$\cdots$	18.833	$\cdots$	$\cdots$	2	
10	RRab	0.59463	19.939	19.535	0.404	0.417	2	
11	F	1.07980	18.182	17.781	0.401	0.414	2	
12	F	1.33366	17.474	17.157	0.317	0.365	1	
14	F	1.72298	17.736	17.233	0.503	0.521	1	
18	E	0.31872	18.528	$\cdots$	$\cdots$	$\cdots$	2	(d)
19	E	0.43382	18.422	18.343	0.079	0.078	2	
20	F	1.49082	17.616	17.192	0.424	0.452	1	
24	F	1.43056	$\cdots$	17.320	$\cdots$	$\cdots$	2	
25	RRab?	0.52774	$\cdots$	19.531	$\cdots$	$\cdots$	2	
26	RRab	0.44636	17.538	17.188	0.350	0.401	1	
27	F	1.50863	17.604	17.020	0.584	0.608	1	
29	RRab	0.47084	18.135	17.856	0.279	0.335	1	
31	O	0.58038	18.137	17.774	0.363	0.371	1	
32	F	2.26841	17.123	16.742	0.381	0.427	1	
34	O	1.93682	16.663	16.233	0.430	0.439	1	
36	F	2.11420	17.505	16.989	0.516	0.548	1	
37	RRab	0.59659	19.884	19.507	0.377	0.393	1	
38	F	1.63004	17.576	17.234	0.342	0.393	2	
42	F	1.33152	17.814	17.449	0.365	0.405	1(B)	
45	RRab	0.52640	19.702	19.451	0.251	0.266	1(V)	
46	F?	2.55475	17.206	16.671	0.535	0.545	2	
48	F	2.29939	17.395	$\cdots$	$\cdots$	$\cdots$	1	
50	F	0.88530	18.653	18.380	0.273	0.308	1	
53	O	0.82857	17.639	17.335	0.304	0.311	1	
55	E	1.35994	18.666	18.673	-0.007	-0.000	1	
57	O	0.72152	17.821	17.494	0.327	0.341	1	

Table 6—Continued

Num	Type	P (days)	$\langle B \rangle$	$\langle V \rangle$	$\langle B \rangle - \langle V \rangle$	$(B - V)_{mag}$	Qual	Notes
59	O	0.86133	17.737	17.392	0.345	0.359	1	
61	?	0.51718	18.757	18.122	0.635	0.635	2	(e)
62	O	0.78903	17.837	17.341	0.496	0.502	1(V)	
65	F	2.00666	17.520	17.015	0.505	0.534	1	
66	O	1.19755	17.244	16.891	0.353	0.363	1	
68	F	2.04065	17.221	16.772	0.449	0.483	1(V)	
70	F	5.65365	16.284	15.702	0.582	0.593	1	
72	O	0.91060	17.761	17.413	0.348	0.361	1	
73	O	1.26752	17.108	16.742	0.366	0.377	1	
74	F	1.52872	17.394	17.044	0.350	0.383	1	
75	F	1.52205	17.595	17.116	0.479	0.493	2	
77	O	1.35339	17.026	16.672	0.354	0.365	1	
80	F	1.28913	17.588	17.194	0.394	0.396	1	
84	O	0.76310	17.672	17.392	0.280	0.295	1	
87	O	0.88342	17.438	17.071	0.367	0.384	1	
88	O	0.81100	17.744	17.380	0.364	0.379	1	
89	RRab	0.45418	17.128	16.880	0.248	0.290	1	
90	O	2.71711	16.377	15.901	0.476	0.481	1	
92	O	0.84835	17.760	17.405	0.355	0.368	1	
95	F	2.61612	17.317	16.735	0.582	0.594	1	
96	F	1.34841	17.990	17.540	0.450	0.473	1(V)	
103	F	1.54345	17.514	17.156	0.358	0.378	2	
105	RRab	0.59722	19.465	19.202	0.263	0.295	1	
107	F	6.49091	15.833	15.286	0.547	0.571	1	
110	O	2.06922	16.808	16.395	0.413	0.420	1	
111	F	1.83433	17.089	16.740	0.349	0.376	2	
113	F	1.08116	18.290	17.945	0.345	0.390	1	
114	O	0.97918	17.192	16.918	0.274	0.285	2	
117	F	3.09329	16.987	16.452	0.535	0.547	1	
124	O	0.86375	17.041	16.925	0.116	0.116	2	(f)
128	O	0.76036	18.099	17.735	0.364	0.377	1	

Table 6—Continued

Num	Type	P (days)	$\langle B \rangle$	$\langle V \rangle$	$\langle B \rangle - \langle V \rangle$	$(B-V)_{mag}$	Qual	Notes
133	F	1.04962	18.048	17.710	0.338	0.368	1	
SSP								
1	F	1.87056	17.074	16.746	0.328	0.379	1	
2	F	2.23245	17.431	16.825	0.606	0.595	2	
3	O	1.17628	17.155	16.840	0.315	0.325	1	
4	E	2.30000	17.408	17.390	0.018	0.024	2	
5	O	1.16093	17.350	16.992	0.358	0.368	2	
6	O	1.29270	16.975	16.660	0.315	0.325	1	
7	O	0.93102	17.492	17.105	0.387	0.395	1	
8	O	2.07345	16.298	15.936	0.362	0.367	1	
9	O	2.29499	16.439	16.044	0.395	0.401	1	
10	F?	1.70068	17.285	16.851	0.434	0.451	2	(g)
11	F	1.64127	17.579	17.149	0.430	0.442	1	
12	RRc?	0.30425	16.806	16.916	-0.110	-0.110	1	
13	F	2.73870	16.707	16.186	0.521	0.526	1	
14	O	1.72946	16.930	16.525	0.405	0.410	1	
15	F	4.18143	16.546	16.019	0.527	0.557	1	
16	O	1.29851	16.821	16.505	0.316	0.321	1	
17	E	3.07225	16.469	16.543	-0.074	-0.075	1	
18	O	1.58453	16.709	16.316	0.393	0.402	1	
19	O	1.20883	16.844	16.504	0.340	0.349	1	
20	E	2.56280	15.322	15.500	-0.178	-0.179	1	
21	O?	1.06209	17.185	16.870	0.315	0.324	2	
22	F?	3.93866	16.808	16.513	0.295	0.298	2	(h)
23	F	1.16736	18.462	18.024	0.438	0.453	2	
24	O?	0.86912	17.501	17.175	0.326	0.337	2	
25	E	1.47070	15.522	15.580	-0.058	-0.058	2	
26	O	2.41914	15.950	15.651	0.299	0.303	1	
27	O?	0.89960	17.908	17.438	0.470	0.476	2	
28	O	1.25427	17.041	16.688	0.353	0.362	1	
29	RRab	0.57382	19.860	19.498	0.362	0.391	1	

Table 6—Continued

Num	Type	P (days)	$\langle B \rangle$	$\langle V \rangle$	$\langle B \rangle - \langle V \rangle$	$(B-V)_{mag}$	Qual	Notes
30	F	3.57270	16.925	16.331	0.594	0.611	1	
31	F	1.87530	17.838	17.292	0.546	0.549	1	
32	O	1.13510	17.227	16.884	0.343	0.349	2	
33	F	2.73273	17.348	16.801	0.547	0.551	1	
34	F	1.51413	17.892	17.435	0.457	0.469	2	
35	E	0.95080	17.913	18.009	-0.096	-0.096	2	(i)
36	F	4.87578	16.304	15.729	0.575	0.602	1	
37	E	1.78000	18.213	16.739	1.474	1.472	2	
38	F	1.30524	18.691	18.243	0.448	0.452	2	
39	F	1.87157	17.463	16.999	0.464	0.479	1	
40	F	1.87780	17.316	16.846	0.470	0.473	1	
41	O	1.05237	17.407	17.067	0.340	0.355	2	
42	O	0.97429	16.613	16.461	0.152	0.154	2	(j)
43	O	1.92178	16.508	16.093	0.415	0.417	1	
44	RRab	0.62042	19.705	19.347	0.358	0.382	1	
45	O	1.13099	17.064	16.770	0.294	0.306	1	
46	O	2.44532	16.324	15.908	0.416	0.421	1	
47	O	1.18244	17.165	16.875	0.290	0.303	1	
48	E	1.25565	17.018	17.119	-0.101	-0.102	2	
49	RRab	0.53193	19.791	19.183	0.608	0.632	1	
50	O	2.31180	16.410	$\cdots$	$\cdots$	$\cdots$	1	
51	O	1.76335	16.537	16.133	0.404	0.415	1	
52	O	1.02323	16.948	16.764	0.184	0.182	2	(k)
53	F	1.32225	17.962	17.416	0.546	0.554	2	
54	O	1.38819	16.690	16.390	0.300	0.304	1	
55	O	1.05222	17.200	16.884	0.316	0.326	2	
56	O	1.71675	16.630	16.281	0.349	0.354	1	
57	O	2.45760	16.208	15.809	0.399	0.403	1	
58	O	3.15021	15.944	15.557	0.387	0.389	1	
59	O	2.31693	16.358	15.959	0.399	0.406	1	
60	F	1.55752	17.783	17.280	0.503	0.522	1	

Table 6—Continued

Num	Type	P (days)	$\langle B \rangle$	$\langle V \rangle$	$\langle B \rangle - \langle V \rangle$	$(B - V)_{mag}$	Qual	Notes
61	E	1.07459	17.522	17.584	-0.062	-0.064	2	
62	F	3.37341	17.028	16.409	0.619	0.623	1	
63	F	3.16083	16.882	16.403	0.479	0.484	2	
64	O	2.00913	16.482	16.072	0.410	0.412	1	
65	F	4.59607	16.720	16.058	0.662	0.687	2	
66	O	1.52643	17.139	16.731	0.408	0.412	1	
67	F	2.64359	16.667	16.192	0.475	0.481	1	
68	O	2.42039	16.381	15.964	0.417	0.423	2	
69	O	0.95101	18.082	17.625	0.457	0.463	2	[l]
70	F	1.36882	17.924	17.522	0.402	0.410	1	
71	F	5.48753	16.518	15.909	0.609	0.612	1	
72	O	1.35233	17.116	16.756	0.360	0.367	1	
73	E	0.79765	$\cdots$	18.489	$\cdots$	$\cdots$	2	
74	O	2.24879	16.613	16.143	0.470	0.476	1	
75	O	3.07698	15.964	15.578	0.386	0.389	2	
76	O	0.83412	17.613	17.282	0.331	0.336	1	
77	F	3.16419	16.802	16.345	0.457	0.490	2	
78	RRab	0.56426	19.992	19.697	0.295	0.317	2	
79	O	2.40705	16.401	16.009	0.392	0.398	2	
80	O	1.17509	17.142	17.203	-0.061	-0.053	1(B)	
81	RRab	0.49061	$\cdots$	19.571	$\cdots$	$\cdots$	1	
82	E	1.52010	17.547	17.069	0.478	0.506	2	
83	O	2.11747	16.681	16.186	0.495	0.497	1	
84	F	6.06841	16.347	15.718	0.629	0.637	2	

[a] Payne-Gaposchkin & Gaposchkin (1966) give P (days)=0.527340 and classify as possible RRab

[b] Probable blue companion (Arp 1960)

[c] Payne-Gaposchkin & Gaposchkin (1966) classify as possible irregular, typing here indeterminate

[d] Much brighter here ($\langle B \rangle = 18.528$) than in Smith et al. (1992) ($\langle B \rangle = 20.1$)

[e] Non-periodic?

[f] Possible blue companion?

[g] Noisy light curve makes typing uncertain

[h] Noise in curves mimicking periodicity?

Table 7.   Reddenings of RR Lyrae Stars

Star	[Fe/H]	ΔS	E_{B-V}
HV12949	-1.15	5.76	0.04
HV2043	-1.50	7.96	0.07
HV2102	-1.18	5.97	0.06
[SSB92] 26	-0.84	3.79	0.09
[SSB92] 29	-1.03	4.97	0.05
[SSB92] 89	-0.93	4.37	0.01

Table 8.   Frequency Distribution of Samples: (a) Present Sample, (b) Smith et al. (1992)

| Period Range | N(fundamental) | | N(first overtone) | |
(log$_{10}$ days)	(a)	(b)	(a)	(b)
-0.3 -0.2	0	0	1	0
-0.2 -0.1	0	0	4	6
-0.1 0.0	1	1	15	8
0.0 0.1	7	5	17	6
0.1 0.2	20	15	11	6
0.2 0.3	21	18	12	8
0.3 0.4	15	9	16	4
0.4 0.5	16	13	3	0
0.5 0.6	15	8	1	1
0.6 0.7	9	5	0	0
0.7 0.8	9	6	0	1
0.8 0.9	4	3	0	0
0.9 1.0	1	2	0	0
1.0 1.1	2	4	0	0
1.1 1.2	1	0	0	0
1.2 1.3	0	1	0	0

Table 9: Coefficients of $P - L$ relations.

Fundamental Mode

76 Stars in B, 77 Stars in V		α	β	
$\langle B \rangle_o$	least squares	-2.50($\pm$0.12)	17.76($\pm$0.05)	$\sigma = 0.23$
	least abs. deviation	-2.58	17.78	$\sigma = 0.19$
$\langle V \rangle_o$	least squares	-2.79($\pm$0.11)	17.47($\pm$0.05)	$\sigma = 0.20$
	least abs. deviation	-2.79	17.45	$\sigma = 0.16$
First Overtone Mode (1-OT)				
62 Stars in B, 60 Stars in V				
$\langle B \rangle_o$	least squares	-2.87($\pm$0.12)	17.10($\pm$0.03)	$\sigma = 0.16$
	least abs. deviation	-2.87	17.10	$\sigma = 0.12$
$\langle V \rangle_o$	least squares	-3.03($\pm$0.10)	16.83($\pm$0.03)	$\sigma = 0.14$
	least abs. deviation	-3.02	16.83	$\sigma = 0.11$

Table 10: W_{BFM} vs. $\log P$

Fundamental Mode				
77 Stars in V		α	β	
W_{BFM}	least squares	-3.63($\pm$0.12)	16.42($\pm$0.05)	$\sigma = 0.21$
	least abs. deviation	-3.55	16.39	$\sigma = 0.14$
First Overtone Mode				
60 Stars in V				
W_{BFM}	least squares	-3.41($\pm$0.12)	15.88($\pm$0.03)	$\sigma = 0.16$
	least abs. deviation	-3.56	15.91	$\sigma = 0.12$

Table 11: $P - L$ Relations for Different Ranges of Period

Fundamental Mode		α	β	
Period > 2 days (43 stars in B, 44 stars in V)				
$\langle B \rangle_o$	least squares	-2.51($\pm$0.21)	17.78($\pm$0.12)	$\sigma = 0.23$
	least absolute deviation	-2.70	17.87	$\sigma = 0.18$
$\langle V \rangle_o$	least squares	-2.60($\pm$0.19)	17.37($\pm$0.10)	$\sigma = 0.19$
	least absolute deviation	-2.75	17.43	$\sigma = 0.15$
Period < 2 days (33 stars in B, 33 stars in V)				
$\langle B \rangle_o$	least squares	-3.47($\pm$0.44)	17.92($\pm$0.09)	$\sigma = 0.22$
	least absolute deviation	-3.86	17.98	$\sigma = 0.18$
$\langle V \rangle_o$	least squares	-3.86($\pm$0.37)	17.67($\pm$0.08)	$\sigma = 0.19$
	least absolute deviation	-3.56	17.58	$\sigma = 0.15$
First Overtone Mode				
Period > 1.4 days (32 stars in B, 31 stars in V)				
$\langle B \rangle_o$	least squares	-3.04($\pm$0.35)	17.18($\pm$0.11)	$\sigma = 0.17$
	least absolute deviation	-3.27	17.27	$\sigma = 0.13$
$\langle V \rangle_o$	least squares	-3.12($\pm$0.31)	16.88($\pm$0.10)	$\sigma = 0.14$
	least absolute deviation	-3.02	16.84	$\sigma = 0.12$
Period < 1.4 days (30 stars in B, 29 stars in V)				
$\langle B \rangle_o$	least squares	-3.50($\pm$0.26)	17.09($\pm$0.03)	$\sigma = 0.14$
	least absolute deviation	-3.20	17.08	$\sigma = 0.11$
$\langle V \rangle_o$	least squares	-3.49($\pm$0.24)	16.82($\pm$0.03)	$\sigma = 0.14$
	least absolute deviation	-3.10	16.83	$\sigma = 0.10$

Table 12: Coefficients of SMC $P - L$ Relations for Udalski et al. (1999a, as revised 2000)

Fundamental Mode		α	β		N
$\langle V \rangle_o$	adopted	-2.78	17.64	$\sigma = 0.26$	464
	original	-2.57($\pm$0.04)	17.49($\pm$0.03)	$\sigma = 0.25$	464
$\langle B \rangle_o$	original	-2.21($\pm$0.05)	17.72($\pm$0.04)	$\sigma = 0.32$	465
First Overtone Mode					
$\langle V \rangle_o$	original	-3.09($\pm$0.05)	17.14($\pm$0.01)	$\sigma = 0.26$	725
$\langle B \rangle_o$	original	-2.93($\pm$0.06)	17.44($\pm$0.02)	$\sigma = 0.32$	729

Table 13: Coefficients of $P - L$ relations: Udalski et al. (1999b) Fields SC10 and SC11

Fundamental Mode		α	β	
107 Stars in B, 107 Stars in V				
$\langle B \rangle_o$	least squares	-2.67($\pm$0.10)	17.85($\pm$0.06)	$\sigma = 0.30$
	least abs. deviation	-2.76	17.91	$\sigma = 0.25$
$\langle V \rangle_o$	least squares	-2.91($\pm$0.08)	17.56($\pm$0.05)	$\sigma = 0.24$
	least abs. deviation	-2.91	17.58	$\sigma = 0.20$
First Overtone Mode (1-OT)				
95 Stars in B, 95 Stars in V				
$\langle B \rangle_o$	least squares	-3.04($\pm$0.18)	17.27($\pm$0.05)	$\sigma = 0.35$
	least abs. deviation	-3.07	17.28	$\sigma = 0.28$
$\langle V \rangle_o$	least squares	-3.20($\pm$0.15)	17.01($\pm$0.04)	$\sigma = 0.30$
	least abs. deviation	-3.28	17.03	$\sigma = 0.24$

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F Cepheids (70)
1−OT Cepheids (58)

Least Squares
Least Abs. Deviation

F Cepheids (76)

Least Squares
Least Abs. Deviation

$\langle B \rangle_\circ$

log P (days)

1−OT Cepheids (62)

Figure showing plot with x-axis "log P (days)" and y-axis "$\langle V \rangle_0$". Legend: "Linear Least Squares" (solid line) and "Quadratic Least Squares" (dotted line). Label: "F Cepheids (77)".

Least Squares (P > 2)
Least Abs. Dev. (P > 2)
Least Squares (P < 2)
Least Abs. Dev. (P< 2)

F Cepheids (77)

Least Squares

Our Sample Least Squares

OGLE F Cepheids (107)
Fields SC10 and SC11

Least Squares

Our Sample Least Squares

OGLE F Cepheids (107)
Fields SC10 and SC11

OGLE 1-OT Cepheids (95)
Fields SC10 and SC11

Least Squares
Our Sample Least Squares

OGLE 1-OT Cepheids (95)
Fields SC10 and SC11